SMC-TR-03-1

AEROSPACE REPORT NO.
TR-2002(8570)-10

Radiometric Calibration Methodology for Near-Infrared Instrumentation

20 October 2002

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This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-00-C-0009 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles Air Force Base, CA 90245. It was reviewed and approved for The Aerospace Corporation by J. A. Hackwell, Principal Director, Space Science Applications Laboratory. Michael Zambrana was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

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SMC/AXE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (*DD-MM-YYYY*)
20-10-2002

2. REPORT TYPE

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Radiometric Calibration Methodology for Near-Infrared Instrumentation

5a. CONTRACT NUMBER
F04701-00-C-0009

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
R, J. Rudy

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Aerospace Corporation
Laboratory Operations
El Segundo, CA 90245-4691

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-2002(8570)-10

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Space and Missile Systems Center
Air Force Space Command
2450 E. El Segundo Blvd.
Los Angeles Air Force Base, CA 90245

10. SPONSOR/MONITOR'S ACRONYM(S)
SMC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
SMC-TR-03-1

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This document describes the selection of a laboratory-based, spectroradiometric standard to provide for the calibration of the near-infrared instrumentation of the Remote Sensing Department of the Space Sciences Application Laboratory. The goal is to provide a source whose spectral emittance is known to better than 1% over the entire near-infrared spectral region (0.8–2.5 µm) and which can be calibrated directly at the National Institute of Standards (NIST). The source selected is a freeze-point cavity blackbody that uses a copper melt with a temperature of 1084.62°C and provides an on-axis effective emissivity of > 0.999. The nominal temperature uncertainty provided by the vendor is ±0.5°C, sufficient to meet our specification. However, through the calibration (and certification) by NIST, the intent is to reduce this value to <0.15°C *with respect to the Nation's primary radiometric standard.* Acquisition of a transfer radiometer will make it possible to extend the calibration to other cavity and variable-temperature blackbodies resident in the department. The freeze-point has the spectral coverage to provide accurate spectroradiometric calibrations in the optical, mid-wave, and longwave infrared spectral regions as well as the near-IR.

15. SUBJECT TERMS
Radiometric calibration, Infrared radiometry, Cavity blackbodies

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Richard Rudy
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER *(include area code)***
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		13	(310)336-5799

Acknowledgments

Helpful discussions were held with K. Irani at Mikron Technologies, R. Waganeck and V. Allen at Electro-Optical Industries, and Dr. B. Tsai at the National Institute of Standards. This work was supported by the US Air Force Space and Missile Systems Center through the Mission Oriented Investigation and Experimentation program, under contract F4701-00-C-0009.

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1. Background

The Remote Sensing department routinely fields a number of cameras, spectrometers, and imaging spectrographs that operate from the optical to the longwave infrared (LWIR). The typical data product from these instruments is provided in units of spectral radiance (e.g., W cm^{-2} μm^{-1}) or irradiance (e.g., W cm^{-2} μm^{-1} sr^{-1}). To assign these units requires that either (1) the sensor have a known calibration over its dynamic and spectral ranges that converts sensor output (usually in volts) to absolute energy units, or (2) that a source with a known absolute spectral energy content be observed contemporaneously with the target under nearly identical conditions. To date, the latter approach is the one most frequently used by the Remote Sensing department. In particular, it is the only method suitable for ground-based astronomical measurements. Since the transmission of the atmosphere is a principal contributor to the measurement uncertainty, the calibration source, like the target, must be above the atmosphere. (However, the absolute flux levels of stars are ultimately linked to laboratory measurements.)

The approach discussed in this document is more concerned with non-astronomical situations. The aim is to provide an accurate laboratory calibration of both the sensor and the luminous sources that might be used as calibration standards in the field. The ideal source to base this calibration upon is a blackbody. For a true blackbody, knowledge of a single parameter, the temperature, describes the energy output (via the Planck equation) at all wavelengths. In the following section, a calibration approach is discussed that utilizes a freeze-point blackbody, a source that very closely matches an ideal blackbody and whose temperature is precisely known.

2. The Freeze-Point Blackbody

Most laboratory radiation sources do not emit a Planckian spectrum. Tungsten lamps, filament heaters, glow bars, etc. have effective emissivities less than unity and which are at least slightly dependent on wavelength. As such they must be calibrated over all wavelengths and all spectral resolutions at which they may be used. The laboratory source that is an exception to this is the cavity blackbody, which utilizes multiple scattering within a hot cavity to produce emissivities very close to unity. Calculations for various cavity shapes and sizes are complex (Chandos and Chandos, 1974) but the underlying principles are relatively straightforward. The radiation seen from a given surface element of the cavity is the sum of the components that it emits and scatters/reflects. If the surface were a perfect radiator the emitted component would equal the desired output, and the scattered component would be zero (since a perfect emitter is also a perfect absorber). In practice, the cavities of commercial blackbodies are generally ceramic or graphite and have surface emissivities in the 0.7–0.9 range. Since, for these materials, the sum of the scattering and emission equals unity (the transparency is zero), it is only necessary for the scattered radiation field to be Planckian for the output to be the true blackbody emission desired. For a completely closed cavity, the radiation would be Planckian at the temperature of the cavity walls regardless of the emissivity of those walls. The necessity for an opening (for viewing) causes a departure in the radiation field from its ideal value. The departure scales approximately as the ratio of the area of the opening to the area of the cavity walls. A theoretical treatment of spherical cavities with circular apertures was published by Gouffe (1945). It yields fairly accurate results (as determined by comparison with detailed numerical treatments) and demonstrates that emissivities >0.999 can readily be obtained for sufficiently large cavities with small openings. While spherical cavities with large diameters and small ports are available, to keep designs compact and minimize the size of the heating elements, cylindrical and conical cavities are more frequently used. These have less favorable area ratios and employ additional means to keep the emissivities high, such as restricting the observer's view of the cavity to the deepest recesses where the radiation density is greater. Although cavity walls are typically roughened, and thus diffuse at optical wavelengths, cylindrical and spherical cavities must take care to ensure that the surface element that is viewed directly does not become reflective at the longer wavelengths since this will reduce the emissivity regardless of the value of the radiation field. Conical cavities do not suffer this problem since they would reflect a view of cavity walls rather than of the outside. With this caveat in mind, it is possible to state that high-emissivity cavities have been produced with values sufficient (>0.9994) that the resulting departures of the radiation field from Planckian are negligible for our purposes.

Of greater concern than the emissivity is knowledge of the actual temperature of the cavity. Readouts can typically be calibrated to ±4°C at T > 1000°C. This alone can result in uncertainties in the flux level at 1 μm of >3%. Thermal probes that can be inserted into the cavities can improve this somewhat, but the readings can be dependent on the position within the cavity. Additional inaccuracies can arise if the cavity heating is not uniform, and, of course, the probes must have their own calibration.

A general remedy for most of these difficulties is found in the freeze-point blackbody. This instrument combines the high-emissivity cavity with the precise temperature defined by the freezing point of a very pure metal. Implementations are commercially available in metals from gallium (freeze point ~30K) to copper (1084K) (Ghaemi, 1996). Table 1 lists the metals for which freeze-point blackbodies are available together with their ITS90 (International Temperature Standards from 1990—see Preston-Thomas, 1990) temperatures. The blackbody cavity is actually surrounded by an envelope of the molten metal (except for the cavity opening) that ensures a very uniform cavity temperature. Freeze-point blackbodies typically come with a controller that takes the cavity up to and through the melting point, holds the temperature above the melting point long enough that all of the metal liquefies, and then slowly reduces the temperature. The melt will then supercool below the melting point and then begin to solidify. When this happens the metal temperature rises and then stabilizes at the freeze point. For a period of 5–20 min, the temperature remains constant within ~0.02K, providing a stable and precisely known radiometric signal. This is the method for radiometric calibration adopted by NIST. The primary radiometric standard for the United States is a freeze-point blackbody utilizing gold (Mielenz et al., 1990a,b).

For our calibration purposes, we have decided to follow the lead of NIST, but have opted to use copper rather than gold. This decision was made strictly on the basis of cost—a fairly large amount of the melt material is required, and the added expense of the gold is ~$16,000. (The radiometric standard of Japan, maintained at the National Research Laboratory of Metrology (NRLM), is also copper). Silver or aluminum were also considered, but because of plans in the near future to extend the calibration effort into the optical, it was desirable to have as high a temperature as possible. For the vendor, EOI (Electro-Optical Industries) of Santa Barbara was selected. This decision was made for two reasons: the shape of the blackbody cavity and the possibility of using additional crucibles. EOI uses a special "reverse conical" cavity that is a superior design to a single cone or cylinder (Chandos and Chandos, 1974). This couples a partial cone to the front (i.e., open) end of a traditional conical cavity. Thus, the diameter of the cavity actually widens for a distance behind the entrance. This prevents any direct view of the slightly cooler portion of the walls near the mouth of the cavity, and increases the ratio of the wall area to that of the opening. An effective, on-axis emissivity of >0.9994 is claimed by EOI. The second feature, the interchangeability of crucibles, allows us to use the same controller and furnace with crucibles containing different metals. This makes it possible to swap out copper for other, lower temperature materials.

Table 1. Freeze-point Blackbody Materials & Their Freezing Temperatures

Material	Freeze Temperature (°C)
Gallium	29.7646
Indium	156.5985
Tin	231.928
Zinc	419.527
Aluminum	660.323
Silver	961.78
Gold	1064.18
Copper	1084.62

At the time of this writing, the copper freeze point from EOI has been ordered. It will arrive with the expectation of providing a temperature within ±0.5K of the ITS value of 1084.62°C. Table 2 gives the concomitant uncertainty in the flux level for a selection of wavelengths. While this level is sufficient for most of our purposes, the unit will be taken to NIST for a direct calibration versus their gold standard (see below).

Table 2. Flux Uncertainties Corresponding to a 0.5°C Temperature Uncertainty at the Freezing Point of Copper (1084.62°C)

Wavelength (μm)	Flux Uncertainty (%)
0.4	0.98
0.7	0.56
1.0	0.39
2.0	0.20
4.0	0.11
7.0	0.07
10	0.06
14	0.05

3. NIST Calibration and Traceability

The National Institute of Standards has the responsibility of establishing and maintaining reference standards, and disseminating the calibrations. The latter process ensures uniformity of standards throughout the user community and is termed "traceability." NIST has a formal definition of "traceability" that is expounded as follows: "Traceability requires the establishment of an unbroken chain of comparisons to stated references. NIST assures the traceability of results of measurements or values of standards that NIST itself provides, either directly or through an official NIST program or collaboration. Other organizations are responsible for establishing the traceability of their own results or values to those of NIST or other stated references."

NIST disseminates the calibration for radiance temperature in a few different ways:

1. They distribute calibrated tungsten-filament lamps that have been compared against their working standard using a transfer radiometer. (The working standard is a variable-temperature blackbody that is calibrated against the gold freeze point.).

2. They calibrate customers' transfer radiometers (usually pyrometers or radiation thermometers) against the working standard.

3. They provide a direct calibration of the customers' freeze point blackbodies versus the gold primary standard. This is accomplished by a direct comparison of the two sources with a transfer radiometer.

Our plan to establish a resident spectroradiometric standard with NIST traceability is to have our copper freeze point calibrated directly against the NIST gold standard. This calibration would be virtually identical to the intercomparison of the United States radiometric standard with that of Japan (O'Brian, Johnson, and Sakuma, 1995). This involved the side-by-side mounting of the NIST gold freeze point and the NRLM copper freeze point on a translational stage that placed one source followed by the other in view of a well-characterized, double-pass monochrometer that served as a calibrated spectroradiometer. The process yielded a radiometric temperature for the copper freeze point within 0.12°C (2sigma) of the ITS90 value for copper. This is a service NIST provides; the estimated cost is $5000–10,000.

Extending the calibration to additional laboratory blackbodies is the topic of the next section.

4. Transferring the Calibration

There are reasons why it might be advantageous to use a blackbody other than the freeze point for a calibration. A temperature much different from that of copper might provide a closer match to that of the target source, or a larger aperture might be needed. Moreover, the freeze point is a sensitive and expensive unit, requires an argon purge, and alternates the freeze plateau (when the temperature is well defined and stable) with periods of cooling and re-melting. For these reasons it is not well suited to field operations where many of the calibrations are performed. Thus, it is planned to extend the calibration to a number of existing variable-temperature blackbodies, using the freeze point, in the laboratory, to calibrate and monitor the repeatability of the field sources. To accomplish this, we will again adopt the method used by NIST and employ a transfer radiometer. The transfer radiometer is a sensor with a narrow field-of-view that looks directly into a blackbody cavity. It has a known band-pass and detector that is highly linear, or whose deviations from linearity are accurately calibrated. At present, a number of commercially available radiation thermometers designed for this purpose are being investigated. They are based on silicon or germanium photodiodes and provide temperature measurement for cavities between 200 and 3000°C. Prices for these transfer radiometers are approximately $9000.

5. Summary

A freeze-point blackbody using a melt of copper has been chosen as the primary spectroradiometric standard for the near-infrared instrumentation of the Remote Sensing department. This blackbody is presently under construction at EOI. After receipt, it will be taken to NIST for direct calibration against the Nation's primary radiometric standard, a freeze-point blackbody implemented in gold. This will provide a very precise measure of any deviations from the expected radiance at the operating temperature as well as direct traceability of the calibration to NIST. Given a half degree uncertainty in the temperature (a value of a quarter to a third of this is anticipated) it will provide a spectroradiometric output that is know to better than 0.5% throughout the near-infrared (0.8–2.5 μm), and will provide a 1% source to wavelengths as short as 0.4 μm. Addition of a transfer radiometer in the future will allow us to extend the calibration (and the NIST traceability) to a number of other laboratory blackbodies, as well as providing a means for monitoring the stability and repeatability of these sources. If it is desirable to have a comparably accurate radiometric source at a lower temperature, for possible work in the MWIR or LWIR, the EOI design allows for the swapping of crucibles, giving access to metals with freeze points as low as 29°C.

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